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HYDROTHERMAL CHARACTERISTICS OF THIN LIQUID FILM FLOW ON HORIZONTAL ROTATING DISK

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ABSTRACT

The paper describes hydrothermal characteristics of liquid flowing on horizontal rotating disk. The liquid was introduced at the centre of the disk in the form of a falling jet. Liquid spread out due to the simultaneous action of surface and body forces and forms a thin film over the disk. The effect of nozzle to plate spacing, fluid flow rate and disk rotational speed on the film thickness, local heat transfer coefficient and local Nusselt number along the radial direction was investigated. It was observed that local heat transfer coefficient and local Nusselt number strongly depends upon flow rate and disk rotational speed and has no influence of nozzle to plate spacing. The study also concludes that the process of heat transfer is intensified manifold by rotating the surface, which will be helpful in the future heat and mass transfer applications.

Keywords: flow on rotating surfaces, heat transfer, hydrodynamics, process intensification, rotating disk heat exchanger, thin film flow.

INTRODUCTION

The important aim in enhancing heat transfer process is to reduce the physical size of heat exchange equipment to minimize capital cost and enhance the operational flexibility and simultaneously reduce energy requirements.

Heat transfer and fluid flow in thin liquid films with rotation, is of particular interest in several mechanical engineering and chemical processing applications. Thin liquid films on rotating surfaces are encountered in the areas of cryogenics, tempering of glass, drying of textile and paper, transpiration cooling and microgravity thermal fluid handling systems. A number of traditional industries have also turned towards the use of rotating disc compact heat exchangers including chemical process industry, power plants and food processing industry.

PRESENT WORK

The present work is concerned with the simultaneous study of hydrodynamics and thermal characteristics of thin liquid film flowing on horizontal rotating disk. The study enlightens the effect of nozzle to plate spacing, fluid flow rate and disk rotational speeds on hydrothermal performance of the system, for fluid flowing on smooth horizontal rotating disk. The experimentally obtained results reveals that fluid flow rate and disk rotational speed strongly affect the thermal and hydrodynamic characteristics of the film. On the other hand, the nozzle to plate spacing does not have significant effect on aforementioned parameters. Flow of thin liquid film on rotating surfaces has become attractive for the scientists, due to increasing applications with the advancement of science and technology. This work will be helpful in the development of space-efficient, light weight and small volume but, compact heat exchangers.

LITERATURE REVIEW

Thermal characteristics of thin liquid films were studied by different investigators. A detail review is presented by Webb and Ma, 1995. Specifically the mathematical analysis was first time conducted by Chaudry, 1964. Further it was improved by Wang and associates, 1989, by introducing two-domain solution at the solid-liquid interface of the rotating disk. In 1978, Carper, et al, analyzed the behavior of convective films formed due to a jet of cooling viscous oil flowing on an isothermal rotating disk to determine the effect of jet Reynolds number, distance between the nozzle and the disk and later on in 1986, Carper, et al studied the effect of Prandtl Number and it was concluded that the centrifugal forces play a vital role in augmenting the heat transfer mechanism and such forces dominates the role of gravitational forces, in the flow process.

Thomas et al, 1990 performed an analytical analysis and presented one dimensional solution of the momentum equation. In similar studies by Vader, et al, 1991 investigated the influence of jet velocity and temperature whereas Steven and Webb, 1991 experimentally determined, the effect of jet Reynolds number, distance between nozzle and plate, as well as jet diameter on heat transfer to fluid, flowing over a stationary and also on the rotating plates. The major scope of their work was focused on the main goal of replacing centrifugal forces with gravitational forces, resulting in an enhanced heat transfer fluxes.

Major contribution in this context has been reported in 1992 and 1993 by Rahman and Faghri and Faghri et al, respectively. These works were more concerned to the stationary surfaces. Aoune and Ramshaw in, 1999 experimentally verified the results by performing a series of heat and mass transfer experiments on the rotating disk.

Later on, remarkable achievement have been made in the work of Ozar, et al, 2003, Rice, 2005, and Basu and Cetegen, regarding the effect of controlling parameters on the intensification of thermal characteristics due to reduction in the thickness of hydrodynamics boundary layers for fluid flowing on horizontal rotating disk. The findings were in accordance with the concepts of Carper, 1986.

The present research wok investigates simultaneous study, regarding the effect of controlling parameters on the intensification of hydrodynamic and thermal characteristics for fluid flowing on a horizontal plain rotating disk, well supported by the experimental data.

THEORETICAL DEVELOPMENT

A number of integral (Cetegen B. M. and Basu, S., 2006), numerical (Faghri et al, 1993) and analytical (Aoune et al, 1999) studies of heat transfer into a thin liquid film on rotating heated disk are reported in literature. The analytical analysis based upon force balance is applied in the present study:

The balance between the body force exerted on the film between $y = y$ and $y = \delta$ and the shear force at $y = y$, gives: (Aoune et al, 1999)

$$\tau = \mu \frac{du}{dy} = \omega^2 r \rho (\delta - y) \tag{a}$$

The solution of above equation is obtained for the boundary condition:

B.C –i At $y = 0$, $T = T_w$ and $\frac{\partial^2 T}{\partial y^2} = 0$, and $u = 0$

B.C-ii At $y = \delta$, $T = T_\delta$ and $\frac{\partial T}{\partial y} = 0$, and $u = u_{max}$

Film thickness is given by:

$$\delta = \left(\frac{3}{2\pi}\frac{Q\upsilon}{r^2\omega^2}\right)^{\frac{1}{3}} \qquad \text{(b)}$$

$$\delta = r\left(\frac{3}{2\pi}\right)^{\frac{1}{3}}\left(\frac{\mathrm{Re}}{T_A^2}\right)^{\frac{1}{3}} \qquad \text{(c)}$$

Fluid average temperature is given by:

$$T_{av} = T_w + \frac{4}{5}\left(T_w - T_\delta\right) \qquad \text{(Present study)} \qquad \text{(d)}$$

$$T_{av} = T_w + \frac{3}{5}\left(T_w - T_\delta\right) \qquad \text{(Aoune et al, 1999)} \qquad \text{(e)}$$

Local heat transfer coefficient substituting the value of T_w - T_{avg} from equation (d):

$$h = \frac{5}{4}k\left(\frac{2\pi r^2\omega^2}{3Q\upsilon}\right)^{\frac{1}{3}} \qquad \text{(f)}$$

$$h = \frac{5}{4}\frac{k}{\upsilon^{\frac{1}{3}}}\left(\frac{2\pi}{3}\right)^{\frac{1}{3}}\left(\frac{T_A}{R_e}\right)^{\frac{1}{3}} r^{-\frac{1}{3}}\ \omega^{\frac{1}{3}} \qquad \text{(g)}$$

Local heat transfer coefficient predicted on the basis of Nusselt theory is given by:

$$h = \frac{heat\ flux}{T_w - T_{av}} = \frac{k}{\delta}\frac{\left(T_w - T_\delta\right)}{T_w - T_{av}} \qquad \text{(Present study)} \qquad \text{(h)}$$

$$h = \frac{heat\ flux}{T_w - T_{av}} = \frac{k}{\delta}\frac{\left(T_w - T_\delta\right)}{T_w - T_i} \qquad \text{(Ozar et al, 2004)} \qquad \text{(i)}$$

EXPERIMENTAL SETUP

A schematic of the experimental setup is shown in Fig. 1. A rotating disk (30 cm diameter and 0.45 cm thick) is mounted on a horizontally oriented (30 cm outer diameter) internal housing, connected to a vertical spindle at the bottom. This small housing is rotated about a vertical shaft in a stationary large (45 cm inner-diameter) external housing, by a variable speed 1.5 k Watts, approximately (2.0 hp) motor. All assembly is made of Stainless steel-316 and is fixed on a heavy frame. Other auxiliary equipment includes 0.45 hp pump, variable area Flow meter, stroboscope, and two feed tanks of 255 liters and 128 liters capacities.

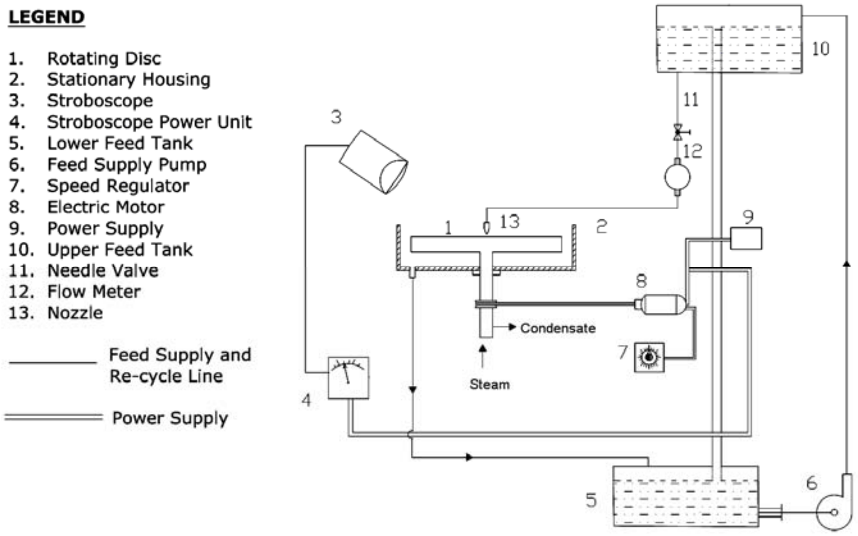

Fig. 1: Schematic of the Experimental Setup

FLOW CIRCUIT

A measured quantity of test fluid (water) was supplied as a falling jet on the center of the disk, through a nozzle of 0.75 cm diameter. The nozzle height was adjusted so that the liquid coming out of the nozzle spread out axi-symmetrically and formed a free surface of the thin film. Care was taken to ensure that the disc was horizontal and fully irrigated. On its way to the periphery, the fluid was heated through the disk surface, maintaining at a constant temperature by condensing steam. The heated fluid collected in the large housing, was returned to the feed tank after passing through a water cooler. Saturated steam was provided through inner pipe in the shaft, to maintain the plate at constant temperature.

Steam condensed in the internal housing and condensate was withdrawn through the annulus pipe in the shaft, and condensate flow rate was calculated by timed-sample collection method.

TEST PROCEDURE

A series of experiments were performed at different rotational speeds and flow rates. The local heat transfer coefficient, film thickness and Nusselt number were evaluated for a case of co-current heat exchanger. The disk surface temperature was measured by a digital laser thermometer (model testo 825 T2) and the average film temperature was measured with a temperature probe, connected to a digital temperature meter. The average fluid temperature was measured with a needle probe, which completes an electrical circuit when the probe touched the liquid.

The typical ranges of operation of the equipment are as follows:

- All measurements were made at radii larger than 2.0cm.
- Rotational speed of motor varies from 100-500 rpm.
- Feed flow rate varies from15 – 30 cm^3/sec.

RESULTS AND DISCUSSION

Experimental data for different set of conditions was collected and results were reported to explore the influence of various parameters on the film thickness and the mechanism of heat transfer. The results are then correlated in form of local heat transfer coefficient and the dimensionless group i.e. local Nusselt number. The results are distributed in two detailed sections, 1) hydrodynamic and; 2) Thermal characteristics of liquid film on the rotating disk.

Hydrodynamic Characteristics

Film Thickness

The liquid film behavior on the rotating disk is controlled by inertial, frictional and centrifugal forces. In the inner region of the disk (near the center), the thickness of film is controlled by liquid inertia, frictional retardation and is of larger thickness, while in peripheral region, centrifugal effects are more dominant and film thickness is lesser in this region. Hence, the film thickness gradually decreases from centre to outer portion of the disk, also reported by, Thomas et al, 1999 and Ozar et al, 2003.

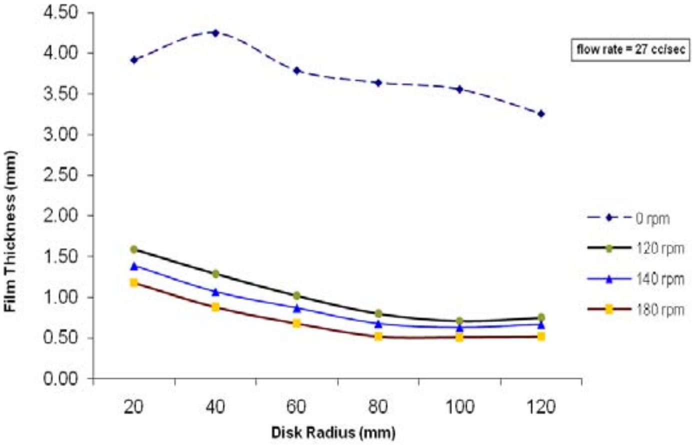

Fig. 2: Film Thickness Distribution along the Radial Direction for Liquid Film Flowing on Smooth Rotating Disk

Comparison of film thickness measured of a stationary disk and at various disk rotational speeds (Fig. 2) show that the film thickness decreases manifold, even at low rotational speeds, due to dominant centrifugal effects. It is also observed that for stationary disk, hydraulic jump appears on the disk and its location depends upon the comparable effect of rotational, inertial and frictional forces.

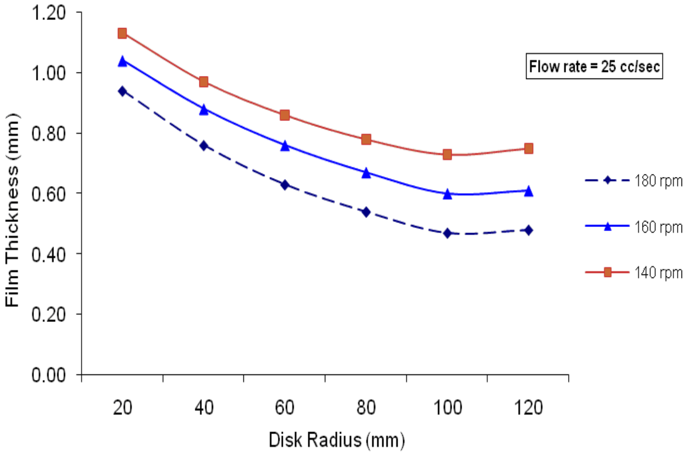

Fig. 3: Film Thickness Distribution along the Radial Direction for Liquid Film Flowing on Smooth Rotating Disk

Fig. 3 describes the effect of rotational speed on film thickness at constant flow rate. It can be seen that film thickness decrease monotonically at all radial locations, by gradually increasing the rotational speeds. It is attributed to the increase in rotational speed that causes more centrifugal effect and the film thickness decreases. However, the effect is more appreciable for high rotational speeds.

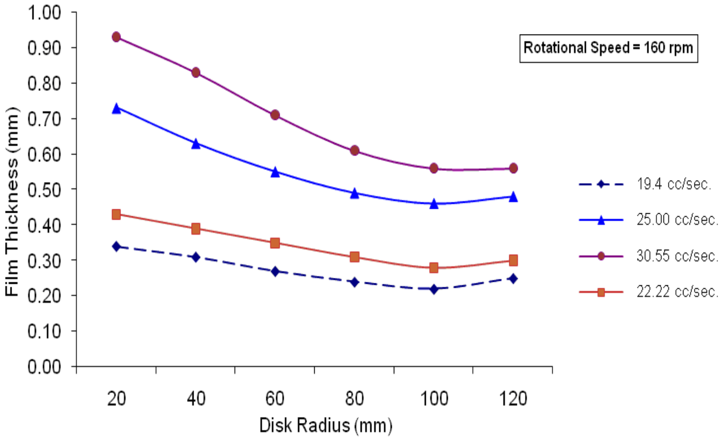

Fig. 4: Film Thickness Distribution along the Radial Direction for Liquid Film Flowing on Smooth Rotating Disk

The effect of increase in flow rate at constant rotational speed is shown in Fig. 4. It is observed that for gradual increase in flow rate, the film thickness increases at all the locations, uniformly because due to increase in flow rate, the frictional retardation of film decrease the velocity of the liquid at high rate, as compared to increase in flow area and hence, the film thickness increase uniformly. Therefore; it is observed that the film thickness is directly proportional to the flow rate and inversely proportional to rotational speed of the disk.

Thermal Characteristics

Disk Surface Temperatures

The disk surface temperature and average fluid temperature were measured at different radial locations by varying flow rates and rotational speeds.

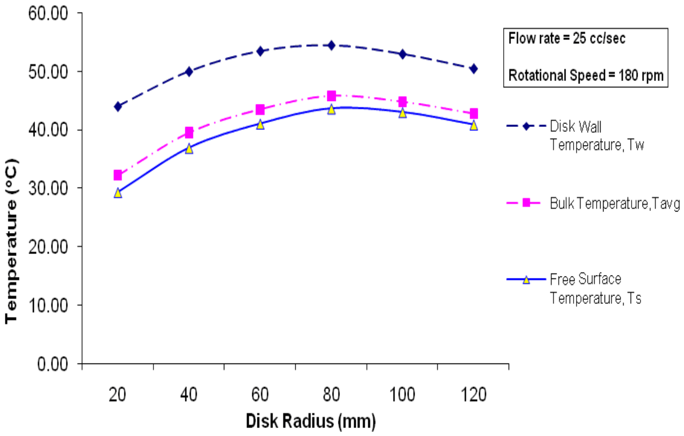

Fig. 5a: Temperature profiles over smooth rotating disk

Fig. 5a demonstrates the variation of disk wall temperature, fluid average temperature and the film free surface temperature along the radial direction and these temperatures increase gradually from center to periphery. The reason is that the rotating surface tremendously reduces the film thickness along the radius which, accelerates the fluid and enhances the rate of heat transfer, also reported by Auone et al (1999). Whereas, near the center, the surface encounters a cold fluid coming from nozzle and the disk temperatures are low in this region.

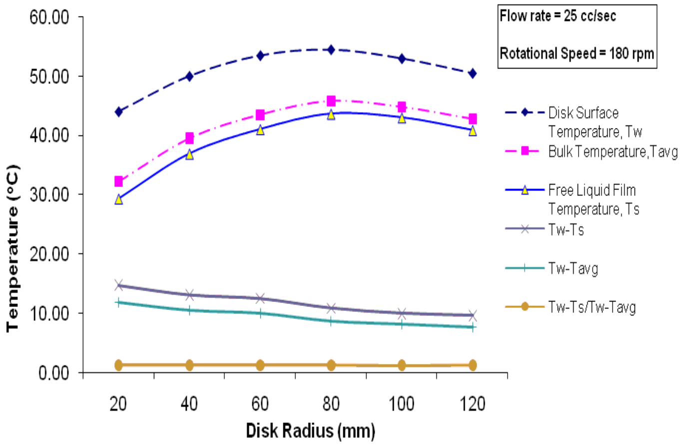

Fig. 5b: Temperature profiles over smooth rotating disk

The difference in local wall temperature and the fluid average temperature, the difference between wall temperature and film free surface temperature, normal to disk at various locations were made and are shown in Fig. 5b. These local temperature differences decrease in the radial direction. It is due to the fact that the film thickness decreases along the radial locations and hence causes less resistance to heat flow, due to which the heat flux to the fluid increases and due to convective heating of the fluid, the disk surface temperature, film average temperature and film free surface temperature approach to each other. While, it is interesting to note that the ratio of these temperature differences remain the same along the radial direction i.e. at 1.25, and the heat transfer is more or less function of film thickness, irrespective of the variation of these temperatures, as explained by Fig. 5b.

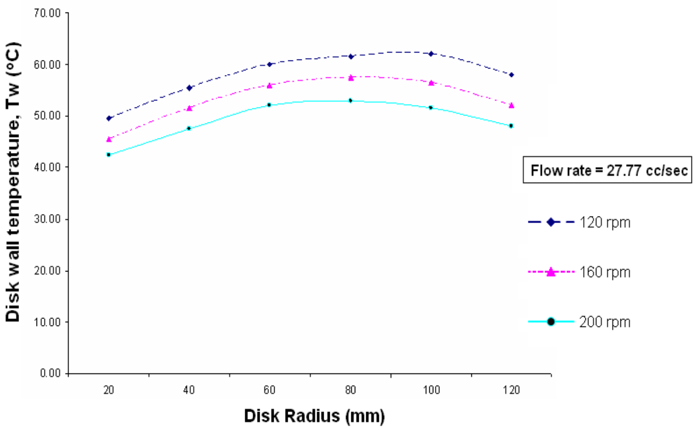

Fig. 5c: Disk wall temperature distribution over a smooth rotating disk

It is also observed that the disc surface temperature at various radial locations is inversely proportional to rotational speed as well as flow rate. It is due to the fact that the surface rotation causes increase in heat flux to the water and the disc surface temperature decreases, where by increasing the flow rate at constant rotational speed, the disk surface temperature decrease, because the larger volume of fluid will take away more heat and the disk surface temperature surface temperature decrease. The increase in film thickness and decrease in heat flux to the fluid is shown in Fig. 5c and 5d.

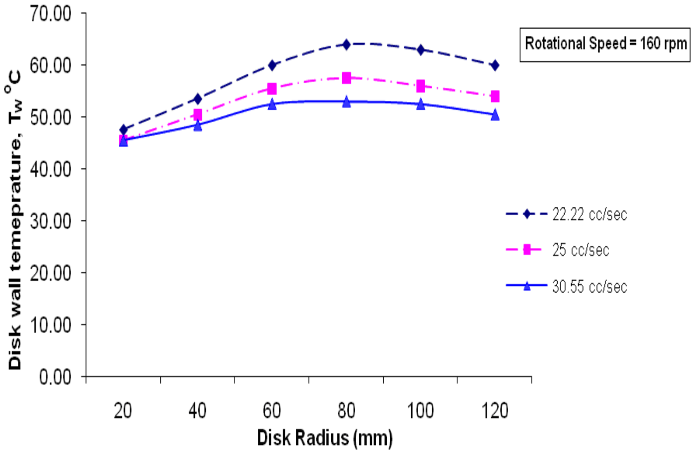

Fig. 5d: Disk wall temperature distribution over a smooth rotating disk

Local Heat Transfer Coefficient

Local heat transfer coefficient is calculated based on heat flux, disk wall temperature, film average temperature and free surface temeprature at various locations, along the radius. The comparison of experimentally measured local heat transfer coefficient (from equation h) and theoretically calculated by equation (f) for typical operating conditions is shown in Fig. 6a. The experimental results are in excellent harmony with the theoretical values. It is also observed that the local heat transfer coefficient increases along the radial direction due to the thininng effect of film by dominating centrifugal effects.

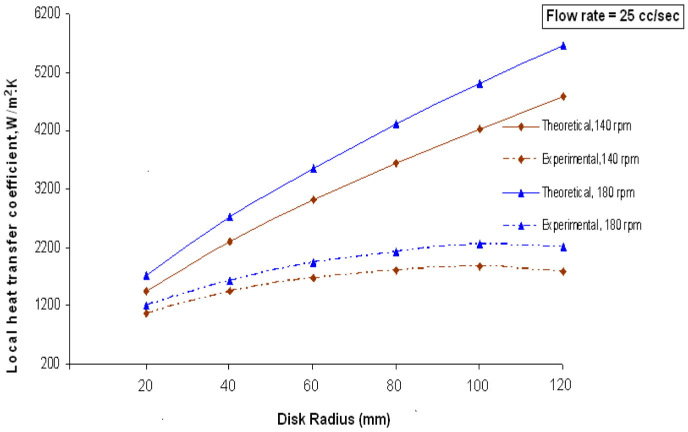

Fig. 6a: Distribution of local heat transfer coefficient along radius on flat plate

The local heat transfer coefficient increases uniformly at all the radial locations by increasing the disk rotational speed at contsnat flow rate and decreases by increasing the flow rate at constant rotational speed, as shown in Fig.6b and Fig. 6c. Since, the hydraulic jump does not appear on the disk surface, consequently the heat transfer coefficients consistently increase in the radial direction.

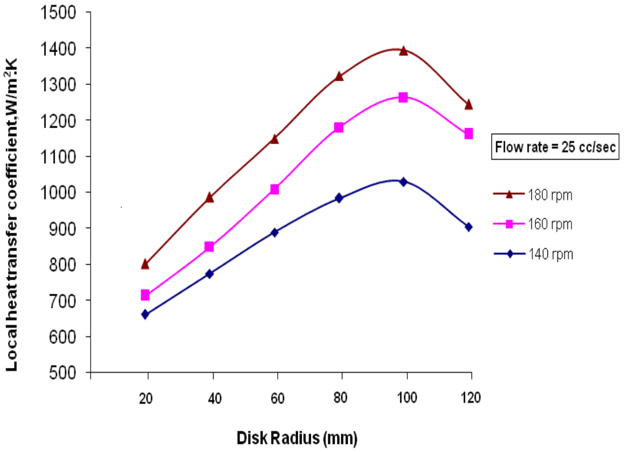

Fig. 6b: Distribution of local heat transfer coefficient along radius on flat plate

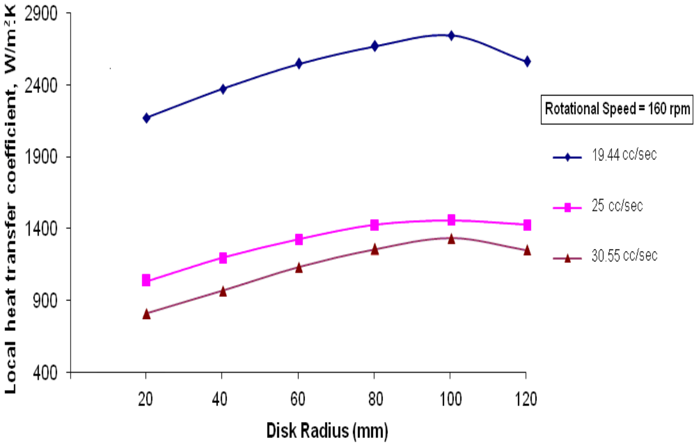

Fig. 6c: Local heat transfer coefficient distribution along radius on flat plate

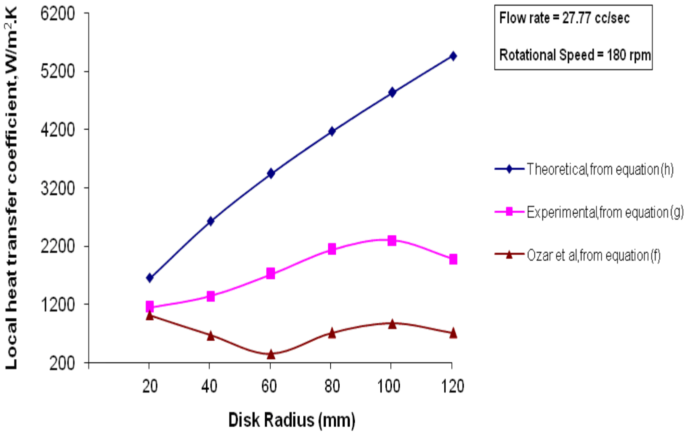

Fig. 6d: Comparison of local heat transfer coefficient along radius on flat plate

Figure 6d demonstrates the comparison of the results of present study for the local heat transfer coefficient calculated by the equation (h) and the correlation (i) presented by Ozar et al, 2003 with that of theoretically obtained by equation (f). It can be seen that the results obtained from the present study are in well accordance with the theoretical, as expected. Therefore, a better confidence limit can be observed in experimental and theoretical results. If, inlet temperature, T_i in equation is replaced by local average temperature, T_{avg} for the computation of local heat transfer coefficient, at specified radial location.

Local Nusselt Number

Local Nusselt number was calculated, based upon the local heat transfer coefficient obtained from equation (h) and from equation (i) an from the equation (f) for particular set of conditions, at various radial locations and the results are represented in following figures (fig. 7a – 7d). A behavior similar to that of local heat transfer coefficient can be perceived and the results show good conformance, similar to local heat transfer coefficient.

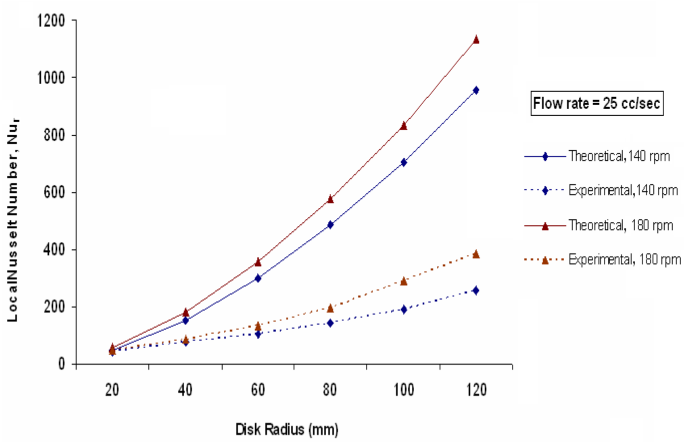

Fig. 7a: Distribution of theoretical and experimental Nusselt number along radius on flat plate

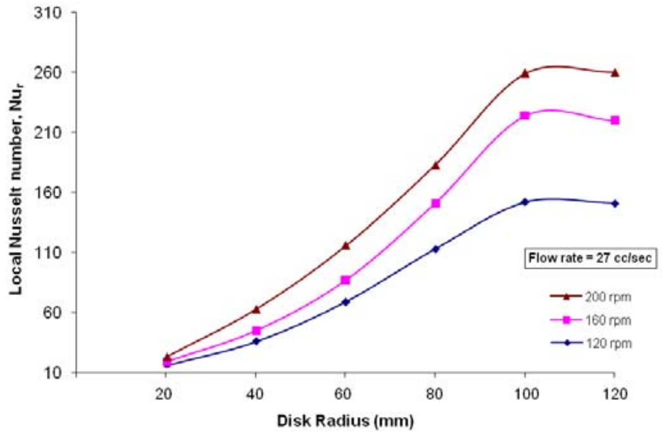

Fig. 7b: Distribution of local Nusselt number along the radial direction on flat plate

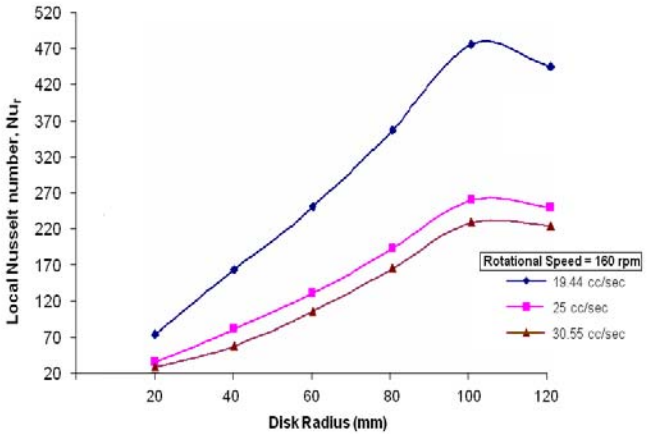

Fig. 7c: Local Nusselt number distribution along radial direction on flat plate

The comparison of the local Nusselt numbers calculated from equation (h) developed in the present study and the correlation (i) developed by Ozar et al, 2003 with that theoretically obtained by equation (h) shows similar behavior as of local heat transfer coefficient, along the radial direction.

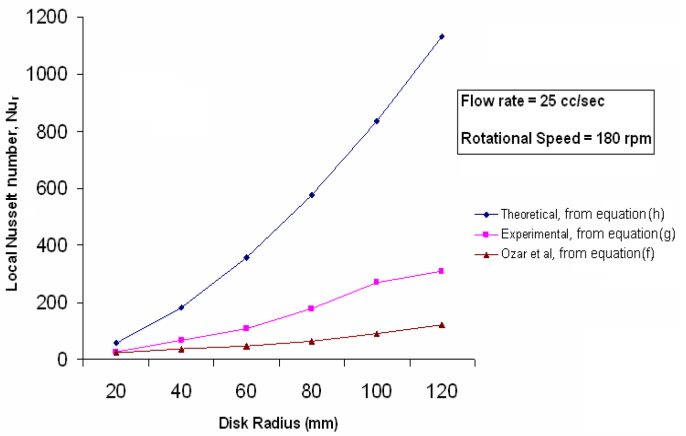

Fig. 7d: Comparison of Nusselt number along radius on flat plate

CONCLUSIONS

Detailed theoretical study was performed and following correction is recommended, in the equation (e). The multiplication factor 3/5 is to be replaced by 4/5. The data based on this corrected model has been plotted and it is evident that a closer agreement exists.

The experimental data has been found coincident with theoretical logic and are contrary to result of similar investigation of Ozar et al. It is suggested that a better confidence limit can be observed in experimental and theoretical data, if inlet temperature, T_i is replaced by average temperature, T_{avg}, in equation (i) at specific radial locations.

REFERENCES

Aoune, A., and Ramshaw, C., 1999, “Process Intensification: Heat and Mass Transfer Characteristics of Liquid Films on Rotating Discs,” *Int. J. Heat Mass Transfer*, 42, pp. 2543-2556.

Basu, S. and Cetegen, B. M., 2006, “Analysis of Hydrodynamics and Heat Transfer in a Thin Liquid Film Flowing over a Rotating Disk by Integral Method” *ASME, Journal of Heat Transfer*, Vol. 128, pp. 217-225.

Carper, H.J., and Defenbaugh, D. M., 1978, “Heat Transfer from a Rotating Disk with Liquid Jet Impingement,” *Proceedings of 6th Int. Heat Transfer Conference in Toronto*, pp. 113-118.

Carper, Jr., H. J., Saavedra, J. J., and Suwanprateep, T., 1986, “Liquid Jet Impingement Cooling of a Rotating Disk,” *ASME J. Heat Transfer*, 108, pp. 540-546.

Chaudhry. Z. H., 1964, ‘‘Heat Transfer in a Radial Liquid Jet,’’, *J. Fluid Mech.,* 20. pp. 501-511.

Faghri, A., Thomas, S., and Rahman, M. M., 1993, “Conjugate Heat Transfer from a Heated Disk to a Thin Liquid Film Formed by a Controlled Impinging Jet,” *ASME J, Heat Transfer,* 115, pp. 116-123.

Ozar. B., Cetegen, B. M. and Faghri, A., 2003., “Experiments on the Flow of a Thin Liquid Film over a Horizontal Stationary and Rotating Disk Surface,” *Exp. Fluids,* 34, pp. 556-565.

Rahman, M. M., and Faghri, A., 1992, “Analysis of Heating and Evaporation from a Liquid Film Adjacent to a Horizontal Rotating Disk,” *Int. J. Heal Mass Transfer*, 35. pp. 2655-2664.

Rice, J., Faghri, A., and Cetegen, B. M., 2005. “Analysis of a Free Surface Film from a Controlled Liquid Impingement Jet over a Rotating Disk including Conjugate Effects with and without Evaporation.” *Int. J. Heat Mass Transfer*, 48, pp. 5192-5204.

Stevens, J., and Webb, B. W., 1991, “Local Heat Transfer Coefficients Under and Axisymmeiric, Single-Phase Liquid Jet,” *ASME J. Heat Transfer,* 113. pp. 71-78.

Thomas, S., Hanky, W., Faghri. A. and Swanson. T., 1990, “One-Dimensional Analysis of the Hydrodynamic and Thermal Characteristics of Thin Film Flows Including the Hydraulic Jump and Rotation,” *ASME J. Heat Transfer*. 112, pp. 728-735.

Vader, D. T., Incropera, F. P., and Viskanta, R., 1991, “Local Convective Heat ‘Transfer from a Heated Surface to an Impinging Planar Jet of Water,” *Int. J. Heat Mass Transfer*, 34, pp. 611-623.

Wang, X. S., Dagan, Z. and Jiji, L. M., 1989, “Heat Transfer between a Circular Free Impinging Jet and a Solid Surface with Non-Uniform Wall Temperature of Wall Heat Flux: I: Solution for the Stagnation Region,” *Int. J. Heat Mass Transfer,* 32, pp. 1351-1360.

Watson, E. J., 1964, ‘‘The Radial Spread of a liquid Jet over a Horizontal Plane,’ *J. Fluid Mech.*, 20. pp. 481-499.

Webb, B. W., and Ma, C. F., 1995,” Single-Phase Liquid Jet Impingement Heat Transfer,” *Adv, Heat Transfer*. 26, pp. 105-217.

NOTATIONS

Roman symbols

h = local heat transfer coefficient, W/m^{2}K
k = thermal conductivity of the liquid, W/m. K
Nu_r = local Nusselt number (hr/k_f)
r = local radius, m
T_{av}, T_{bulk} = average fluid temperature, ˚C
T_w = local disk surface temperature, ˚C
T_i = inlet fluid temperature, ˚C
T_s = free surface temperature of the liquid film, ˚C
T_A = dimensionless Taylor number, $r^2\omega/\upsilon$
R_e = dimensionless Reynolds number, $Q/r\upsilon$
Nu_r = dimensionless Nusselt number, $h \times r/k$

Greek symbols

δ = film thickness, m